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Making Clean Gasoline The Effect on Jet Fuels

PL015R1

Robert W. Salthouse

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Executive Summary

MAKING CLEAN GASOLINE: THE EFFECT ON JET FUELS

Persistently high concentrations of carbon monoxide and low-altitude ozone in the air of the Nation's major urban centers led Congress in the 1990 Clean Air Act Amendments to mandate changes to the composition of gasoline and diesel fuel. Those gasoline composition changes will require major modifications to the manufacturing processes that refiners use to produce gasoline for sale in much of the United States. Since petroleum refining is a complex process involving a variety of chemical interactions between final products, many observers – including DoD fuel managers – fear possible declines in the quality and availability of jet fuel. Currently, the Air Force plans to convert from naphtha-based JP-4 jet fuel to distillate-based JP-8 jet fuel.

Despite the extent of the required refinery process modifications, however, we conclude that neither the quality nor the availability of jet fuel purchased by the military is likely to change significantly.

Among the provisions of the 1990 Clean Air Act Amendments is a limit on aromatic compounds in gasoline, which led to fears that refiners would divert excess aromatic compounds into jet fuel. However, refiners are unlikely to do that for two reasons. First, existing jet fuel specifications – “smoke point” and a maximum aromatic ceiling – already limit the refiners’ ability to increase the volume of aromatics in jet fuel. Second, the manufacture of aromatics to improve gasoline performance is expensive. Rather than divert expensive manufactured aromatics, refiners will merely produce less of them.

Using less aromatics will reduce the amount of conventional gasoline produced using refinery “conversion” processes and will simultaneously increase the amount of distillate fuels produced – jet fuel, diesel fuel, and home heating oil. Distillates come from a different “cut” of crude oil than gasoline and other naphtha cuts. Therefore, distillate fuel production could increase the availability of distillate jet fuels such as

JP-5 and JP-8. On the other hand, naphtha-based JP-4 fuel, used by the Air Force, competes directly with gasoline for naphtha "feedstocks" and may become more expensive. Jet fuel quality is unlikely to change more than marginally as a result of gasoline reformulation.

We recommend that the Air Force proceed with its plans for the gradual conversion from JP-4 to JP-8 for its domestic operations. The legally mandated gasoline reformulation is unlikely to reduce the quality and availability of kerosene-based jet fuels such as JP-8 and JP-5. Also, reformulation makes this an opportune time to switch away from using naphtha-based JP 4, which because of its greater volatility than JP-8, is less safe and poses environmental problems. Further, we recommend that the Defense Fuel Supply Center continue to monitor the availability and the quality of jet fuels supplied by domestic refiners.

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CHAPTER 1

FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

In this chapter, we summarize the findings and conclusions that are presented in greater depth in the chapters that follow. We describe the effect of recent changes in environmental laws and regulations on the quality and availability of military jet fuels in the United States. In particular, we explain the extent that changes in fuel manufacture will affect the Air Force's planned domestic conversion from naphtha-based JP-4 jet fuel to distillate-based JP-8 jet fuel.

POLLUTION FROM MOBILE SOURCES

The main targets of the 1990 Clean Air Act (CAA) Amendments are excess ozone levels and airborne toxic compounds. Ozone, a lung irritant, causes respiratory problems. Carbon monoxide (CO) and benzene are both motor vehicle emissions that are listed by the U.S. Environmental Protection Agency (EPA) as toxic air pollutants; benzene is a known carcinogen. Suspended toxic particulate matter are a direct health threat.

The role of motor vehicles in producing air pollution has been long recognized. In particular, researchers know that motor vehicles are responsible for almost all CO emissions and about 40 percent of the ozone in urban areas. Vehicles are also a major source of toxic air pollutants such as benzene, which is present in gasoline and is also produced by engine combustion.

More efficient combustion, achieved by increasing the oxygen content of gasoline, can reduce the amount of CO produced. For that reason, the 1990 CAA Amendments mandate oxygenated gasoline in CO "nonattainment" areas.¹ While oxygenation reduces CO emissions from older vehicles, its usefulness is less certain in newer engines with sophisticated combustion and emissions controls. In addition,

¹The CAA Amendments of 1977 directed that areas of the country be designated attainment or nonattainment areas with respect to specific pollutants, depending on whether they met the previously established National Ambient Air Quality Standards.

the less CO produced, the more carbon dioxide is formed, which has been implicated in global warming.

The precise mechanisms whereby gasoline and diesel fuel emissions produce ozone are not clearly understood. We know, however, that the combination of hydrocarbons, also known as volatile organic compounds (VOCs), with oxides of nitrogen (NO_x) in the presence of sunlight is one such mechanism for producing ozone. The EPA has already attempted to reduce VOCs by promulgating rules that mandate lower gasoline vapor pressure in the summer months. The new CAA Amendments go further by reducing the amount of ozone-forming compounds in gasoline and also mandating reduced emissions of both VOCs and NO_x .

Modeling by the Joint U.S. Auto Industry Research Program indicates that changing the composition of gasoline may reduce ozone levels in ozone non-attainment areas. The preliminary study concludes that the ozone produced by cars and light trucks can be cut from about 33 percent currently down to 5 to 9 percent by the years 2005 through 2010.

Ozone reduction would result from a combination of vehicle turnover and changes in fuel composition. The study examines four gasoline changes: reduced aromatics, added oxygenates, reduced boiling range, and reduced olefins. Interestingly, the first two changes – mandated by the CAA Amendments – produced no conclusive effect on ozone formation, while the latter two clearly reduced ozone. Specifically, the study assumed an olefin limit of 5 percent maximum by volume (current gasoline contains about 20 percent) and a maximum boiling range of 280 degree fahrenheit ($^{\circ}\text{F}$) (currently around 330°F to 430°F). The study also found that reducing gasoline sulfur content significantly reduces emissions of hydrocarbons, CO, and NO_x . (The study did not include sulfur limits in its model of ozone reduction, however.)

We must keep in mind that in passing the 1990 CAA Amendments, Congress did not take as many actions as were originally proposed. Specifically, they did not limit the boiling range of gasoline, nor did they limit olefin content. Those are potential actions for the future. Although motor vehicle emissions are generally reduced by making gasoline from a narrower boiling range of crude oil, Congress probably rejected that limitation in the latest bill because it would reduce the yield of gasoline from crude oil, thereby increasing imports.

FINDINGS

The 1990 CAA Amendments require domestic refiners to make major changes to gasoline formulations and make lesser changes to diesel fuel in the coming years. By 1992, only so-called *oxygenated gasoline* – fuel that meets a minimum oxygen specification – can be sold during the winter months in the approximately 40 regions that fail to meet Federal CO standards. By 1995, only *reformulated gasoline* – fuel that meets various additional content and emissions restrictions – can be sold in the nine urban areas that violate Federal ozone standards. (The new law also mandates some changes to diesel fuel, including lower sulfur content.)

In order to meet the law's requirements, petroleum refiners will have to procure new refining process units and modify others. Estimates of the total cost for U.S. refiners to comply with the new provisions run between \$24 billion and \$42 billion.² Refining is a complex industrial process with numerous interactions between individual process units; changes to the way that gasoline and diesel fuel are produced will affect other petroleum products. The question is, to what extent and in what directions will those changes affect jet fuels?

CONCLUSIONS

The 1990 CAA Amendments were signed into law in November 1990. The U.S. refiners have not yet finalized their plans for producing reformulated fuels or are unwilling to divulge them prematurely. Refiners have not had time to build new process units or to modify existing ones. Additionally, many refiners and process engineers are keeping their plans secret because they are vying for competitive advantage in the new world of environmental-friendly fuels.

Nevertheless, we can reach some preliminary conclusions at this point based on a combination of published reports on likely refinery modifications and our own modeling of the refinery process with a particular eye to effects on jet fuels and other middle distillate fuels.

²J. R. Hall, "U.S. Refiners Move into Another Challenging Technical Era," *Oil and Gas Journal*, October 21, 1991, p. 58.

M. E., Scherr, et al., "Clean Air Act Complicates Refinery Planning," *Oil and Gas Journal*, May 27, 1991, p. 68.

T. Witoshkin, and G. Yepsen, "Refiners Have Options to Deal with Reformulated Gasoline," *Oil and Gas Journal*, April 28, 1991, p. 71.

Some refiners have started construction on, or have announced plans for, new oxygenate plants and other refinery modifications. Therefore, the general outlines of their plans have now been made public. More importantly, we know enough about the general modifications that refiners need to make to allow us to model the process in general terms.

The mandated gasoline changes will affect the availability of other products, including military jet fuels, by changing the relative yields of products refined from crude oil. That is, manufacturers of oxygenated and reformulated gasolines will modify refinery product yields at those refineries that choose to, or are forced to, manufacture them.

In order to manufacture reformulated gasoline, the refining industry must reduce the proportion of aromatic compounds, a class of hydrocarbons, that it currently blends into gasoline. At the same time, refiners must increase the percentage of oxygen (O_2) in order to make both oxygenated and reformulated gasoline. Just about the only way to reduce aromatics and increase O_2 content simultaneously, without reducing octane, is to substitute oxygenates: alcohols or ethers made from alcohols. Adding ethers, the preferred choice, raises the O_2 content and also replaces the octane lost when aromatics are removed from gasoline. The refining industry, as a whole, may choose to purchase or import most of the ethers it needs or it may choose to manufacture them in its own plants.

What happens to the aromatic compounds when the added ethers displace them? The short answer is that refiners are unlikely to manufacture them in the first place. Only a small percentage of the aromatics found in finished fuels derive directly from crude oil; most are created during the manufacture of gasoline. Refiners desire aromatic compounds because they increase the octane of gasoline. They manufacture them primarily in two processes: reforming and catalytic cracking. Of the two, the reforming process is for various reasons the most likely to bear the brunt of the coming changes, although both processes are likely to be modified at least to some extent. The primary result of those modifications will be to reduce the volume of aromatic compounds below the mandated level. There will be no "excess" aromatics to "dump" into jet fuel or into any other refinery product above the levels now current.

Furthermore, the percentage content of aromatic compounds is explicitly limited by military jet fuel specifications. Although the aromatic content of purchased jet fuel currently falls well below those specifications, another specification, the "smoke point," places even stricter limits on aromatic content. To the limited extent that it addresses the issue, the literature on gasoline reformulation reflects a general consensus that existing jet fuel specifications do not permit the addition of significantly more aromatic compounds to jet fuels. Thus, if aromatics do exceed gasoline limits, they are likely to be converted into more useful compounds.

Jet Fuel Quality and Availability

We conclude that the refinery changes needed to meet the 1990 CAA Amendments' fuel requirements will not affect jet fuel production. We also conclude that diesel fuel production is likely either to remain the same or to increase (displacing some imports of jet/diesel precursors). Even a scenario that has the industry reducing crude oil runs to compensate for increased ether imports will leave diesel fuel production unchanged.

In addition, we find that jet fuel quality will change only slightly, if at all. Any changes are likely to be negligible and well within specifications.

Further reinforcing our conclusions is the fact that our analysis was based on worst case scenarios that have domestic refiners producing 100 percent reformulated gasolines. Since our extreme scenarios produced few and extremely small changes in the quality of jet fuels and other distillate-range fuels, we can be fairly confident that the actual changes will affect jet fuels even less. In addition, those changes will phase in slowly up to 1995.

Nevertheless, some caveats should be addressed. The future is uncertain; refiners are only now starting to make the changes necessary to produce and market reformulated gasoline, and there will probably be some unanticipated consequences. In addition, our analysis focuses upon changes due to reformulated gasoline. Other changes are also taking place at the same time. For instance, changes in crude oils could change jet fuel qualities. Such changes, however, tend to occur fairly slowly and are to a great extent under the control of refiners. The U.S. refiners, for example, tend to use heavier crude oils than overseas refiners because they have invested more

heavily in conversion equipment to produce more barrels of gasoline from heavy crude oils, which are cheaper than lighter crude oils.

RECOMMENDATIONS

We recommend that the Air Force proceed with its plans for the gradual conversion away from naphtha-based JP-4 jet fuel to kerosene-based JP-8 jet fuel. The coming changes in the refining industry will not adversely affect either kerosene-based jet fuel quantity or quality.

While we foresee no particular cause for alarm, we recommend that the Defense Fuel Supply Center (DFSC) continue to monitor the availability and the quality of jet fuels supplied by domestic refiners.

CHAPTER 2

REQUIREMENTS OF THE CLEAN AIR ACT AMENDMENTS FUEL

In this chapter, we summarize the requirements of the 1990 CAA Amendments that affect petroleum products. In Chapter 3, we examine the potential refining process changes necessary to meet those requirements.

CLEAN AIR LEGISLATION PRIOR TO 1990

By the standards of environmental regulation, domestic clean air legislation has a relatively long history. The first Federal legislation was the Air Pollution Control – Research and Technical Assistance Act of 1955. This was followed by the CAA of 1963 and subsequent Amendments in 1965, 1967, 1970, 1977, and most recently, in 1990. Because previous clean air legislation had proved largely ineffective, the 1970 Amendments substantially rewrote the CAA and established a significant Federal role in the regulation and enforcement of air quality.

The 1970 CAA Amendments gave considerable authority to the newly created EPA to establish and enforce implementing regulations. In particular, the Amendment required EPA to establish National Ambient Air Quality Standards (NAAQS), expressed as concentrations of specific air pollutants. In implementing the law, the EPA designated the pollutants to be controlled, and they published criteria documents that set forth the health effects of, and the ambient air standards for, those pollutants. The EPA further defined 247 Air Quality Control Regions, which have been rated either as “attainment” or as “nonattainment” areas for each of the designated “criteria pollutants.” The CAA called for the states to achieve the mandated NAAQS through state implementation plans (SIPs). While those SIPs had to provide for compliance by both stationary and mobile pollution sources, the CAA focused upon major stationary sources, defined as those that emit more than 100 tons of a designated pollutant per year.

REGULATING MOBILE SOURCES

Government officials have known about the role of mobile sources – automobiles, trucks, and airplanes – in generating air pollution since the 1950s.

Local government officials in Los Angeles were the first to attempt to regulate automobile emissions. (Despite all efforts, however, Los Angeles today still has serious ozone and CO problems.) The 1965 CAA Amendments, known as the Motor Vehicle Air Pollution Control Act, was the first attempt at the Federal level to control vehicle emissions by authorizing Federal emission standards to be imposed upon new motor vehicles. Although the 1970 Amendments concentrated on stationary air pollution sources, they went further than the previous Amendments in regulating mobile sources. The 1990 CAA Amendments continue and expand upon those earlier mobile source regulations. A major shift in this latest clean air legislation is the specification of gasoline content in geographical areas having unacceptably high levels of ozone and CO.

Under the early statutes, the states were generally free to choose their own mix of controls over stationary and mobile pollution sources to attain the NAAQS. Control over mobile sources under the 1970 and 1977 Amendments included the testing and inspection of motor vehicles. In addition, Section 202 of the 1970 Act directed the EPA to regulate motor vehicle emissions that "cause, or contribute to, air pollution which may reasonably be anticipated to endanger public health or welfare."¹ The EPA set standards for vehicle emissions of CO, hydrocarbons, NO_x, and particulate matter. Those standards resulted in the automobile emission control systems that first appeared in the early 1970s. While the regulations mainly controlled emissions and mandated engine (or exhaust system) modifications, the first fuel modifications also resulted from the earlier Amendments. They allowed the EPA to regulate gasoline lead content and vapor pressure (volatile hydrocarbons).

NEW MOBILE SOURCE REQUIREMENTS

Because nonattainment remains a problem, the 1990 CAA Amendments have gone much further than earlier legislation in mandating the content of motor vehicle fuels. The latest Amendments basically mandate two sets of gasoline formulations: oxygenated gasoline and reformulated gasoline. Although the Act lays out fuel requirements in considerable detail, it gives EPA some leeway.

¹Public Law 91-604.

Oxygenated Gasoline

Oxygenated gasoline must contain a minimum percentage of O₂ by weight, which should allow it to burn more cleanly and completely in automobile engines, thus reducing CO production. The law sets the minimum oxygen content for gasoline sold in CO nonattainment areas, i.e., areas that fail to meet CO standards. Generally, the restrictions apply only during the winter months. Table 2-1 lists the serious and moderate nonattainment areas. Beginning on 11 November 1992, the gasoline sold during the winter in those areas must contain a minimum of 2.7 percent O₂ by weight. However, the EPA may grant extensions of up to 2 years due to inadequate gasoline supply or inadequate distribution. On the other hand, looking further into the future, the EPA may increase the minimum oxygen content to 3.1 percent for areas that do not come into compliance with CO standards by December 2000.

Table 2-2 compares oxygenated gasoline's minimum O₂ requirement with the current actual average O₂ content, which is much lower. (The last column of the table summarizes some of the more extensive requirements of reformulated gasoline, which are discussed below.)

Reformulated Gasoline

Gasoline sold in the nine ozone nonattainment areas listed in Table 2-3 must meet a larger number of requirements, including the mandated fuel "formula" summarized in Table 2-2. While that reformulated gasoline also requires a minimum oxygen content, the requirement is slightly less strict than the requirement for CO nonattainment areas. (The stricter requirement applies, of course, in areas such as Los Angeles and New York City, where the multiple requirements actually overlap.) While total aromatic content is limited to 25 percent by volume, aromatic compounds consist of benzene plus all other aromatics. Benzene is specifically limited to only 1 percent by volume. All lead additives will be prohibited from being blended with reformulated gasoline by the Act; heavy metals other than lead are also prohibited unless the EPA grants a waiver.

TABLE 2-1
CARBON MONOXIDE NONATTAINMENT AREAS

Serious nonattainment areas	
Los Angeles, Cal. (CMSA) New York, N.Y./N.J./Conn. (CMSA) Spokane, Wash.	Steubenville/Weirton, Ohio/ W.Va. Winnebago Co., Wis.
Moderate nonattainment areas	
Albuquerque, N.Mex. Anchorage, Alas. Baltimore, Md. Boston, Mass. (CMSA) Chico, Cal. Cleveland, Ohio (CMSA) Colorado Springs, Col. Denver/Boulder, Col. Duluth, Minn./Wis. El Paso, Tex. Fairbanks, Alas. (non-MSA) Fort Collins, Col. Greensboro/Winston Salem/High Point, N.C. Hartford, Conn. (CMSA) Josephine County, Ore. (non-MSA) Klamath County, Ore. (non-MSA) Las Vegas, Nev.	Medford, Ore. Memphis, Tenn./Ark./Miss. Minneapolis/St. Paul, Minn./Wis. Missoula County, Mont. (non-MSA) Modesto, Cal. Philadelphia, Pa./N.J./Del. (CMSA) Phoenix, Ariz. Portland/Vancouver, Ore./Wash. (CMSA) Provo/Orem, Utah Raleigh/Durham, N.C. Reno, Nev. Sacramento, Cal. San Francisco/Oakland/San Jose, Cal. (CMSA) Seattle/Tacoma, Wash. Stockton, Cal. Syracuse, N.Y. Washington, D.C., Md./Va.

Source: R. C. Scherr, G. A. Smalley, Jr., and M. E. Norman, "Clean Air Act Complicates Refinery Planning," *Oil and Gas Journal*, May 27, 1991, p. 69.

Note: CMSA = consolidated metropolitan statistical area; MSA = metropolitan statistical area.

TABLE 2-2
NEW GASOLINE REQUIREMENTS

Gasoline components	Current level	New requirements	
		Oxygenated	Reformulated
O ₂ (minimum weight percentage)	0.2	2.7	2.0
Benzene (maximum volume percentage)	1.5 – 2.0	N/A	1.0
Aromatics (maximum volume percentage)	32	N/A	25

Note: N/A = not applicable.

TABLE 2-3
OZONE NONATTAINMENT AREAS

Extreme nonattainment area	
Los Angeles, Cal. (CMSA)	
Severe nonattainment area	
Baltimore, Md. Chicago, Ill./Ind./Wis. (CMSA) Houston/Galveston/Brazoria, Tex. (CMSA) Milwaukee/Racine, Wis. (CMSA)	Muskegon, Mich. New York, N.Y./N.J./Conn. (CMSA) Philadelphia, Pa./N.J./Del. (CMSA) San Diego, Cal.

Note: CMSA = consolidated metropolitan statistical area.

Source: R. C. Scherr, G. A. Smalley, Jr., and M. E. Norman, "Clean Air Act Complicates Refinery Planning," *Oil and Gas Journal*, May 27, 1991, p. 70.

The 1990 CAA Amendments attempt to reduce air pollution in two ways. First, they deal with engine inputs by mandating reformulated (and oxygenated) fuels. Second, they deal with engine outputs by setting the strict emission standards summarized in Table 2-4. Those standards are set in relation to the emission from 1990 gasoline. While NO_x emissions must not increase above the 1990 standard, VOC emissions must decrease by 25 percent from the 1990 standards, at least during

the high ozone season. In addition, total aggregate toxic air pollutant emissions must also fall 15 percent below 1990 levels.²

TABLE 2-4
VEHICLE EMISSION RESTRICTIONS

Vehicle emissions	Minimum percentage decrease from 1990	
	1990s	2000
NO _x	0	0
VOCs	15	25
Toxic air pollutants	15	25

Note: VOC = volatile organic compound.

Other CAA Requirements

The 1990 CAA Amendments also contain some additional fuel requirements. Gasoline vapor pressure is limited. All gasolines must contain detergents by January 1995. Lead additives will be banned nationwide by January 1996.

The 1990 CAA Amendments contain antidumping provisions that prohibit degrading the gasoline pool outside of the nonattainment areas below the 1990 average standards. Those provisions are designed to prevent refiners from moving benzene and other aromatics from reformulated gasoline into conventional (non-reformulated) gasoline.

In addition to gasoline, the 1990 CAA Amendments mandate certain diesel specifications, which are to be met by October 1993. Diesel fuel sold nationwide must have a maximum sulfur content of 0.05 percent by weight and a minimum cetane number of 40.

²Currently, the EPA defines the following gasoline components as toxic air pollutants: benzene, 1,3-butadiene, acetaldehyde, formaldehyde, and polycyclic organic matter. (Benzene, therefore, is controlled both going into the engine and coming out of it.)

REGULATORY IMPLEMENTATION

In order to implement the 1990 CAA Amendments, the EPA must issue specific rules for refiners to follow. According to the law, refiners must supply oxygenated gasoline to CO nonattainment areas by November 1992. Those rules require that gasoline must contain 2.7 percent oxygen by weight during the critical winter months. The legal requirements for the content of reformulated gasoline are more complex; the EPA is still working on its final regulations. In the meantime, the EPA has issued its interim "Simple Model" for reformulated gasoline, to be effective from 1 January 1995 through 1 March 1997. The EPA's "Complex Model," will succeed the Simple Model. Essentially, the Simple Model calls for a minimum of 2 percent oxygen by weight, a maximum of 1 percent benzene by volume, no heavy metals (unless waived), and a Reid vapor pressure³ in the summer of between 7.2 and 8.1 depending on the class of gasoline. In addition, no individual refiner can exceed the sulfur content, olefin content, and 90° F boiling point values of its average 1990 gasoline sales.

EXTENT OF THE REFORMULATED/OXYGENATED GASOLINE MARKET

In summary, the new gasoline specifications are limited to certain nonattainment areas. Oxygenated fuels with the single O₂ content restriction must be sold to the widest market: about 40 CO nonattainment areas. The more restrictive reformulated fuels are limited to nine ozone nonattainment areas. Nevertheless, the CO and ozone nonattainment areas are large, mostly urban with high population concentrations. That is hardly surprising because large numbers of motor vehicles produce a lot of pollution, specifically CO and ozone.

Several factors indicate that oxygenated and reformulated fuels will be sold in an even wider area than the law requires. First, retail gasoline stations and distribution channels are generally configured to carry three grades of fuel at most. Refiners are phasing out gasoline lead additives faster than required by the EPA partially because of the logistical problems of carrying several octane grades in both leaded and unleaded formulations. Therefore, refiners are likely to distribute oxygenated and reformulated (or only reformulated fuels) to more than just the nonattainment areas. Second, the law allows another 87 areas with marginal, moderate, or serious ozone problems to require reformulated gasoline; many of them

³A measure of volatility, named after the inventor of the test apparatus.

are likely to do so. Third, large refiners may seek a competitive advantage in switching wholeheartedly to reformulated fuels to gain positive public relations advantages and to anticipate future regulations.

Estimates of the extent of the reformulated gasoline market range from about 10 to 100 percent more than the legislated minimum.⁴ Since the Amendments will require about 25 percent of domestic gasoline production to be reformulated, it is likely that between 30 and 50 percent of gasoline provided by domestic refiners will be made to meet the law's requirements. Some observers believe that 100 percent of U.S. gasoline may be reformulated by the year 2000.⁵

⁴A. K. Rhodes, "U.S. Refiners Scramble to Meet Reformulated Gasoline Mandate," *Oil and Gas Journal*, January 27, 1992, p. 23.

⁵Hall, *op. cit.*, p. 58.

CHAPTER 3

REFINING PROCESS CHANGES FOR REFORMULATED AND OXYGENATED GASOLINE

To produce the volumes of reformulated gasoline that will be needed in the future — estimated at anywhere from 30 percent to 50 percent of the total domestic gasoline pool — domestic refineries must undertake a number of profound changes over the next few years. As detailed in Chapter 2, the major changes to gasoline content will be a reduction in benzene and other heavier aromatic compounds, and an increase in oxygen content. To reduce aromatics, refiners are likely to modify the operations and configurations of the major aromatic-producing processes: the fluid catalytic cracking (FCC) unit and the catalytic reformer. To increase oxygen, refiners are already starting to add new units for producing oxygenates, mainly methyl tertiary butyl ether (MTBE). Refiners will also modify other processes. In this chapter, we outline the potential refinery changes. In Chapter 4, we discuss the effect of those changes on the quantity and quality of jet fuel and other distillate fuels. For those readers not familiar with refinery processes, Appendix A provides a general overview of them.

GASOLINE MANUFACTURING PROCESSES

Gasoline is the major petroleum product in the United States, comprising close to 50 percent of domestic refinery output. U.S. refiners, as a group, have more gasoline production capacity than any other country. That high gasoline yield means that refiners must rely heavily on conversion units that break down heavy, less valuable hydrocarbons into lighter gasoline components. Gasoline components also require extensive processing in order to meet customers' quality specifications. One significant quality specification is the need for high-octane values to avoid premature ignition, "knocking," in engine cylinders. Knocking reduces efficiency and damages engines.

Gasoline is not a single chemical; it is a blend of many different hydrocarbon molecules, all of which fall within a certain band of boiling points. Gasoline manufacture consists of a number of processes that produce the compounds needed

plus a blending operation that produces a mix meeting the required specifications for octane, volatility, and other characteristics. Refiners carefully optimize their processing units in order to produce just the right mix of compounds within the necessary boiling range, a mix that meets specifications at the lowest possible cost. Since refiners blend various different compounds to make gasoline, they speak in terms of the "gasoline blending pool."

The major refinery processes that supply the gasoline blending pool components are the following:

- *Catalytic reforming:* Employs heat, pressure, and platinum catalysts to "reform" straight-run and other naphtha compounds into higher octane aromatic compounds. Reforming improves gasoline octane while producing little change in boiling range.
- *Fluid catalytic cracking:* Uses heat, pressure, and chemical catalysts to break straight-run, heavy gas-oils into lighter gasoline-range molecules.
- *Alkylation:* Produces high-octane compounds from light compounds that are otherwise too volatile for blending directly into gasoline.
- *Hydrocracking:* Improves quality by "saturating" the hydrocarbons and virtually eliminating the production of olefins and aromatics, compounds with less stable double bonds. Hydrocracking produces both high-quality gasoline and distillate blendstocks. This is essentially catalytic cracking with the presence of hydrogen.

Neither FCC nor hydrocracking conversion processes convert all of their feed into gasoline components; their output ends up in petrochemicals and distillate fuels as well. Products too heavy for blending into distillate fuels are usually recycled through the conversion units, a process called "recycling to extinction." (The third major refinery conversion process, thermal cracking, breaks down very heavy hydrocarbons and normally plays little part in gasoline production.)

Catalytic reforming and alkylation do not appreciably change the boiling points of the input products; they are primarily quality improvement processes. With the advent of the 1990 CAA Amendments, however, some such quality improvements now involve quality tradeoffs. Notably, catalytic reforming increases octane by increasing the volume percent of aromatic compounds, including benzene. Because those compounds are limited in reformulated gasoline, refiners will have to modify the processes that manufacture them.

Catalytic Reforming

The catalytic reforming units will be hardest hit by the 1990 CAA Amendments because the required reduction in the proportion of benzene and other aromatics in reformat (reformer output) causes reduction in its octane-blending ability. One way to reduce reformat's aromatic content is to reduce the severity – the temperature and pressure – of reformer operations. Reducing severity, however, also reduces octane. That lower octane can be corrected by partially replacing reformat with high-octane oxygenates in the gasoline blending pool.

Another way to reduce the proportion of aromatics, particularly benzene, in reformat is simply to remove them, or the compounds that tend to produce them (precursors), using fractionation (distillation). Refiners can *prefractionate* the reformer feed to remove benzene precursors or they can *postfractionate* the reformat to remove benzene. Light reformat, in particular, tends to have higher benzene content than the heavier reformates and is a prime target for postfractionation.

Prefractionation and postfractionation, however, both raise the question of what to do with the separated materials; they also tend to reduce octane. If a suitable market exists, refiners can sell the benzene or benzene precursors (methyl cyclopentane and cyclohexane) for petrochemical manufacture. Otherwise, refiners will have to convert those compounds into usable streams. They can route benzene to their hydrocracking or hydrotreating units to saturate the benzene with hydrogen and return it to the gasoline pool, or they can modify benzene via isomerization (a relatively mild chemical change that rearranges atoms within a molecule) or alkylation processes. Depending on the chemical changes, intermediate product prices, and refinery setup, refiners can direct the resulting products to petrochemicals, gasoline, or distillate fuels.¹

As we have noted before, refineries are extremely complex manufacturing operations. Every change has many ramifications. Reformers normally produce the excess hydrogen that is needed for the hydrocracker. Reducing reformer severity reduces hydrogen production and will require some refineries to purchase hydrogen from other sources or add more hydrogen manufacturing capacity. If benzene and

¹As stated previously, jet fuel specifications and the 1990 CAA Amendment's diesel fuel restrictions preclude adding increased benzene or other aromatics to distillate fuels, including jet fuels.

other aromatics are removed from reformat, additional hydrogen will be needed to convert them into environmentally benign, saturated compounds.

Fluid Catalytic Cracking

Since FCC units are necessary to meet the relatively high U.S. demand for gasoline, the FCC unit will remain the most important processing unit in most U.S. refineries under the 1990 CAA Amendments. Eighty-seven percent of all domestic refineries have FCC units. However, FCC gasoline blendstocks contain about 30 percent aromatics by volume. Unless other changes offset that, refiners will have to modify their FCC operations, although probably not to the extent that they will have to alter catalytic reforming.

The FCC units will probably become more flexible, using a wider variety of specialized catalysts to better regulate output. In addition, refiners will likely increase their ability to separate FCC products in order to redirect light olefins – propylenes and butylenes – to oxygenate production units. Some such FCC olefins will need further processing in isomerization units to convert them into the specific isomers – molecular configurations – of propylenes and butylenes that oxygenate processes require. We discuss the specifics of oxygenate production below.

Many refinery experts have suggested modifying FCC operations to reduce the volume of the heavier FCC output currently sent to gasoline blending because those components have a higher percentage of aromatics than lighter FCC output. However, a refiner's ability to divert those heavy "cycle oils" away from gasoline to the distillate blending pool is strictly limited by jet fuel and diesel fuel specifications, particularly smoke point and aromatic limits in jet fuel, cetane index in diesel fuel, and the stability of both fuels. One possibility for dealing with excess heavy cycle oils is that refiners will separate or recover the aromatics from those heavy cycle oils for petrochemical processing. Ultimately, refiners may also send heavy cycle oils back through the FCC unit or, better yet, to the hydrocracker where the added hydrogen will saturate the aromatics, converting them into more environmentally benign hydrocarbons.

Nevertheless, despite new catalysts and the separation of certain products for oxygenate and petrochemical processing, it is likely that refiners will ultimately

reduce aromatic production by reducing the temperatures and pressures under which the FCC unit operates (i.e., by reducing FCC severity).

Alkylation

Alkylation units produce gasoline blendstocks that are naturally low in aromatics (less than 1 percent). They also have attractive vapor pressure and octane values. However, reformulated gasoline production will force alkylation units to compete with oxygenation units for butylene since that compound can be used to manufacture either alkylate or oxygenate. Like alkylates, oxygenates have good vapor pressure and octane values. Despite the competition for olefin feedstocks, however, some refinery experts believe that the importance of alkylation will increase in the future because of its importance for gasoline quality.

Hydrocracking

Hydrocracking produces high-quality intermediate products for blending into gasoline, jet fuel, and other distillate fuels. The outputs – hydrocrackates – are ideal for blending into reformulated gasoline because they have low sulfur content and extremely low levels of benzene and other aromatics. Refiners may also use hydrocracking to process refinery streams that are rich in aromatics. Hydrocracking (and hydrotreating, a less intense process) will also be needed to produce low-sulfur diesel fuel as required by the 1990 CAA Amendments.

Oxygenate Production

To increase the volume of O₂ in gasoline from the current level of about 0.2 percent to the CAA Amendments' newly required 2.0 percent or 2.7 percent, refiners will have to add alcohols or ethers to gasoline, which have high oxygen content. MTBE, with an O₂ content of about 18 percent and a relatively high-octane rating (109), is the strongest candidate.

The reaction of isobutylene with methanol produces MTBE. Isobutylene – an olefin with four carbon atoms and one double bond – is found in some intermediate refinery streams and can also be produced from paraffins and other olefins by isomerization. In particular, refiners can obtain increased volumes of isobutylene by separating and isomerizing those olefins with 4 carbon atoms, normally produced by

the FCC unit. Polypropylene – normally sent to petrochemical processing – is another promising feedstock for oxygenates.

Besides crude oil, natural gas is another source of isobutylene for making MTBE and ethyl tertiary butyl ether (ETBE). Although natural gas consists overwhelmingly of methane, it also contains small amounts of heavier hydrocarbons known as natural gas liquids (NGL).² Oxygenate manufacturers can extract butane and isobutane from NGL for conversion into isobutylene via isomerization.

Many of the domestic oxygenate units announced so far are internal refinery units and are sized to use isobutylene already produced by the refinery's FCC and isomerization units. That isobutylene is added to purchased methanol to produce MTBE, the most attractive oxygenate. One manufacturer is building a plant to take advantage of its existing petrochemical processes by making MTBE using chemical feeds and butane from natural gas. Isomerization will convert butane into the necessary olefins.

Despite current construction activity and future plans, the domestic oxygenate supply is unlikely to be sufficient to meet refiners' demand in the short to medium term. MTBE capacity has grown from about 50 thousand barrels per day (kBD) in 1986 to over 120 kBD today. Even though domestic MTBE production is still growing and is expected to reach between 275 kBD and 330 kBD by 1994, that capacity falls short of estimated 1994/1995 demand, which ranges from about 590 kBD to 650 kBD.³ While oxygenate demand depends on the degree to which additional state and local jurisdictions will require reformulated gasoline, even the lower estimates require imports to make up the difference.

Other oxygenates besides MTBE are unlikely to contribute significant additional capacity in the short term. Ethanol capacity, which can produce ETBE, has changed very little; there have been no announced new plants and only one announced plant expansion. Tertiary amyl methyl ether (TAME) units could also help make up the shortfall eventually, but no new plants have been announced.

²NGL and its cousin, liquified petroleum gas (LPG), are somewhat imprecise terms that generally refer to light hydrocarbons above the methane boiling point. NGL refers to hydrocarbons derived from natural gas, while LPG (mostly propane) is made from either natural gas or crude oil. Despite their names, neither is a liquid at normal pressure and temperature.

³R. O. Jones and T. J. Lareau, *Meeting the Oxygenate Requirements of the 1990 Clean Air Act Amendments*, American Petroleum Institute, Research Study #058, June 1991.

CONCLUSIONS

Our findings regarding the likely effects of the 1990 CAA Amendments on refinery production lead us to two major conclusions.

First, refiners will be forced to reduce conversion as a source of gasoline blendstocks, at least to some extent. That is, the gasoline yields of both catalytic cracking and FCC units will decline. The net effect will be lower conversion from crude oil to gasoline and, thus, higher distillate yields. Our analysis shows that the effects will not necessarily be large, but they will make distillate fuels more plentiful in relation to gasoline.

Second, the addition of oxygenates, made partially from purchased alcohol, to gasoline will reduce the percentage of gasoline blending components from crude oil, thus decreasing the need for crude oil runs. Some observers initially feared that replacing crude oil with oxygenates would result in lower yields of both gasoline and distillate. However, our analysis shows that reduced conversion is more than enough to offset those effects. More recent studies agree with our conclusions.

CHAPTER 4

THE EFFECT OF REFINERY CHANGES ON JET FUEL QUALITY AND AVAILABILITY

What is likely to happen to jet fuels as a result of the legally mandated, major changes that U.S. refineries are about to undertake?

We conclude that, despite far-reaching gasoline production changes, the quality and availability of jet fuels will *not* change significantly; overall, distillate availability may even increase. Even JP-4, which competes most directly with gasoline for naphtha feedstocks, is unlikely to experience major changes. We base these conclusions on our review of recent literature, the opinions of petroleum experts, and our own computerized modeling of refinery operations. We provide literature citations in the selected bibliography and detail the results of our computerized refinery modeling in Appendices B, C, and D.

Refinery modeling is essential because of the large number of complex interactions involved. In order to place the widest possible envelope around our model results, we base our model scenarios on extreme worst cases: 100 percent oxygenated/reformulated gasoline throughout the U.S. and the most stringent gasoline volatility standards throughout the year. Even in those extreme cases, the changes to jet fuel quality and availability prove to be insignificant.

JET FUEL QUALITY AND AVAILABILITY

Table 4-1 summarizes our model's measurement of JP-4 and kero-jet quality changes that will result from implementation of the 1990 CAA Amendments. The JP-4 quality remains the same, while the changes to kero-jet fuels are relatively minor. According to our worst case models, kero-jet (commercial jet, JP-5, and JP-8) density and flammability may change slightly, but the changes are extremely small and well within specifications. When we increase kero-jet production, assuming total conversion from JP-4 to JP-8, the quality changes are also insignificant.

TABLE 4-1

PROSPECTIVE CHANGE IN JET FUEL PROPERTIES UNDER THE NEW LAW

Properties	Percentage change under new law	
	JP-4	Kero-jet
Density (API gravity)	0	(0.2) – 0.7
Sulfur content	0	0
Flammability (flash point)	0	(1.4) – 4.0

Note: API gravity is the standard measure of density in the oil industry; it is inversely proportional to specific gravity.

FINDINGS

Our conclusions regarding key fuel quality and availability are based on the following findings, which we expand upon in the rest of this chapter:

- Aromatics are expensive to produce; refiners will not waste them by “dumping” them, thereby reducing product quality.
- Jet fuel is a high-value product that, after gasoline, is the last to feel the effects of changes in feedstock availability or other changes. That is, gasoline and the jet fuels have first priority for receiving high quality, high-value hydrocarbons.
- JP-4 competes directly with gasoline for light hydrocarbons in the gasoline boiling range. However, JP-4 comprises less than 2 percent of total domestic refinery output. The JP-4 can be blended using hydrocarbons from a relatively wide boiling range.
- Kero-jet fuel uses feedstocks that are different from gasolines. Thus, kero-jet fuel is directly influenced little by changes in gasoline blending, although there can be indirect effects.
- Reductions in catalytic conversion and catalytic reforming to lower the aromatic content of gasoline increase distillate yields relative to gasoline.
- Lower crude oil runs caused by partial replacement of gasoline feedstocks with alcohols (directly or in the form of ethers) are more than offset by increased distillate yields.

Aromatics Are Expensive to Produce

Refiners produce aromatic compounds with expensive platinum catalysts using the reforming process. Refiners undertake that expense to improve gasoline octane, particularly in the absence of lead additives. Refiners will not create excess reformat that would reduce the quality of jet fuel and other distillate fuel. They will reduce reformer throughput instead.

Aromatic compounds are so valuable, in fact, that refiners often recover naturally occurring aromatics from naphtha, kerosene, and heavy gas-oil using a solvent extraction process. Refiners remove those aromatics either to sell as petrochemical stocks, to improve product characteristics, or both. Removing aromatics improves the smoke point of kerosene and the lubricating oil properties of heavy gas-oils. The hydrocarbons left behind include "raffinate," an aromatic-free light- to medium-weight hydrocarbon that refiners blend into JP-4 or distillate fuels. Thus, refiners have already faced the problem of "excess" aromatics and have solved it without damaging product quality.

Jet Fuel Has Priority for High-Quality Blendstocks

Because gasoline and jet fuels are high-value refinery products, refiners assign them top priority for the highest quality blending products. Moreover, gasoline and jet fuel compete directly for only some intermediate products.

Refiners blend naphtha-based jet fuel, JP-4, from relatively light hydrocarbons, with a higher vapor pressure and volatility index than conventional commercial kero-jet fuels. JP-4 competes with gasoline for some of those hydrocarbons. For example, JP-4 competes with gasoline for light naphtha, which can be blended directly into either product. Gasoline and JP-4 compete indirectly for medium naphtha, which can be blended directly into JP-4 or sent to the reformer to improve gasoline octane.

Military JP-4 is a highly flexible product that can contain a variety of hydrocarbons within a relatively wide boiling range, including heavy naphtha, butane, jet-hydrocrackate from the hydrocracker, kerosene, light naphtha, and medium naphtha. Gasoline processes have little interaction with JP-4 blending. While JP-4 may contain some raffinate, the hydrocarbons left after running straight-run kerosene or naphtha through the aromatic extraction unit, it does not compete for

intermediate products from the catalytic cracker or the FCC unit because of the olefins and aromatics they contain.

Conventional kero-jet fuels do not compete directly with gasoline for their blendstocks, but they do compete indirectly since refiners can choose to send middle distillates to either jet fuel blending or to a conversion unit to make gasoline components. Like JP-4, kero-jet does not compete for intermediate products from the catalytic cracker or the FCC unit. As the name implies, kero-jet fuel usually contains a very high proportion of kerosene, which is not a gasoline blendstock. Kerosene is a straight-run product that may go through some quality improvement processes, particularly hydrotreating to remove sulfur. Excess volumes of kerosene beyond that blended into jet fuel are either sold directly as a product or blended into other distillate or heavier fuels to improve viscosity. Military JP-5 and JP-8 fuels are essentially commercial kero-jet fuels with a few additional specifications, including the use of supplementary additives.

Even when jet fuels and gasoline compete for the same hydrocarbons, such as naphtha, sufficient amounts are likely to be available to meet both needs, since refiners direct naphtha to other uses — diesel fuel and home heating oil — only if they have excess remaining after gasoline and jet fuel blending. That is, a reduction in naphtha volume will affect home heating oil first, diesel fuel second, and jet fuel and gasoline last.

Refiners control their various processes in order to maximize production of their highest value products. They pay particular attention to their output of gasoline and jet fuel and are unlikely to let production of naphtha or distillate drop to a point that threatens the production of either.

JP-4 Production Is Relatively Small

Refiners can make a lot of changes without having much effect on JP-4 because so little is produced relative to other products. JP-4 comprises less than 2 percent of total domestic refinery output compared with about 46 percent for gasoline. Some individual refiners, of course, produce large amounts of JP-4 in relation to their overall output; for them, the interactions will be significant.

In addition to light naphtha, JP-4 and gasoline compete directly for light- to medium-weight hydrocracker products. Nevertheless, since JP-4 comprises such a

small fraction of total domestic output, the competition for feedstocks is not particularly fierce. Moreover, even when refiners give gasoline precedence, JP-4 is a flexible product that can be produced from a variety of hydrocarbons within a relatively wide boiling range.

Kero-jet Uses Different Feedstocks

Kero-jet fuels – JP-5, JP-8, and commercial jet fuels – are manufactured by blending medium-weight hydrocarbons, mainly kerosene, that are generally higher than the allowable boiling range for gasoline. Refiners generally blend in as much kerosene as possible up to the allowable sulfur limit and then add heavy naphtha and jet hydrocrackate from the hydrocracker. Kerosene is a straight-run compound; its most valuable use is for jet fuel blending; any excess beyond the sulfur limit is blended to other distillates and residual fuel oil to control viscosity.

Reduced Conversion Increases Relative Distillate Yields

While kero-jet fuel does not compete directly with gasoline for blendstocks, changing operating parameters, such as the proportion of gas-oils directed to the FCC unit versus the hydrocracker, have the potential to change the volume of products available for jet fuel blending. Fortunately for jet fuel, the probable refinery changes will likely increase the availability of jet fuel components. FCC units and, most notably, catalytic reformers, will use fewer distillate-range hydrocarbons and thus increase the yield of hydrocarbons in the kero-jet range relative to gasoline.

Our analysis indicates that sufficient naphtha and other hydrocarbons will remain available for blending high-quality jet fuels. Moreover, we do not foresee any major change in other distillate products.

Lower Crude Oil Runs Will Not Reduce Distillate Availability

The addition of oxygenates like alcohols and ethers will replace crude oil. Alcohols can replace crude oil directly, and ethers can replace them partially because of the alcohols used in their manufacture. This has led to speculation that distillate yields, including jet fuel yields, would drop correspondingly. We find, however, that a drop in distillate and jet fuel yields is unlikely to occur because the countervailing drop in refinery conversion increases distillate yields by a greater amount.

We find that sufficient hydrocarbons will be available to produce high-quality gasoline, jet fuel, and distillate fuels despite lower crude oil runs. Our model tests two cases: both higher reformer throughput and lower reformer throughput versus the base case. Crude oil runs and thus straight-run product yields are down in both cases. Nevertheless, even when crude oil runs are reduced by one million barrels per day, net distillate yields actually increase. (We assume that distillate output is unchanged, reducing purchases of unfinished distillate instead.)

Table 4-2 illustrates the net effect on total naphtha availability of both model cases. The table shows volumes relative to the total naphtha available in the base case, which is indexed to 100. As the table illustrates, the U.S. refiners can maintain the same volume of naphtha in the JP-4 blending pool in all three cases; naphtha sent to kero-jet increases in one case. While lower crude oil runs yield less straight-run naphtha in both Cases 1 and 2, refineries still have sufficient naphtha for jet fuel blending and for the catalytic reformer. Even when crude runs are down (less straight-run naphtha) and catalytic reformer throughput is up (more naphtha turned into reformate), sufficient naphtha remains to supply the jet fuel blending pool; other distillate fuels absorb the shortage.

When a refinery has less total naphtha available, the less valuable, less quality-sensitive distillate fuels suffer. Even then, sufficient alternate hydrocarbons are available so that total distillate yields increase even when straight-run yields are down and reformer use is up.

OTHER CONSIDERATIONS

Jet fuel customers fear that refiners will continue to pare away at their "quality giveaway," the margin by which the refiner's products actually exceed specifications. Refiners continually try to come as close to the fuel specification as possible. In some instances, however, it is difficult to meet one specification without violating another. For example, refiners will have difficulty adding more aromatics, even when they already fall below the maximum aromatic limit: in doing so they may exceed another specification — the "smoke point."

Although we find that the refinery changes necessary to satisfy the 1990 CAA Amendments will not, by themselves, reduce jet fuel quality, that does not mean that quality cannot, or will not, decline from other causes. For example, refiners might purchase crude oils with a higher aromatic content. Nevertheless, we have no

TABLE 4-2
NAPHTHA USE

Source/use	Percentage volume		
	Case 1	Base case	Case 2
Reformer utilization ^a	68.5	66.7	62.1
Source			
Straight-run	94	98	97
Aromatic recovery	4	2	4
Total naphtha	98 ^b	100	101 ^b
Use			
Jet fuel	12	11	11
To reformer	78	76	68
Petrochemicals	7	7	7
Diesel/heating oil	1	6	15
Total naphtha	98 ^b	100	101 ^b

^a Percent of total usable capacity.

^b Base case total naphtha indexed to 100.

particular reason to believe that other factors exist that are likely to cause quality either to decline or to improve.

RECOMMENDATIONS

The future of petroleum products is always uncertain. Crude oil supplies have been a source of volatility in the past and may prove to be so again in the future. The 1990 CAA Amendments, by imposing radical new quality requirements on gasoline, add more uncertainty. However, all else being equal, we do not expect the CAA Amendments to cause problems for jet fuel quality or availability in the coming decade. Nevertheless, while the future is still unpredictable, the picture is becoming clearer with respect to reformulated gasoline. The EPA has issued its Simple Model, which will be in effect until 1997. Judging by the plans that have been made public, MTBE appears to be the oxygenate of choice.

We set up our model to address the most extreme negative possibilities. From this and other evidence, we conclude that the advent of reformulated and oxygenated gasolines will leave jet fuel quality and availability basically unchanged.

We recommend that the Air Force proceed with its phased plan to convert from JP-4 to JP-8 fuel. While the fuel suppliers may change, the U.S. refining industry as a whole should have the capacity and capability to continue to supply jet fuels that satisfactorily meet DoD's performance requirements.

We also recommend that the DFSC continue to monitor the quality of the jet fuel that it purchases, since reformulated and oxygenated gasolines are not the only changes likely to occur in the refining industry. The DoD should also be prepared for the enactment of even more stringent clean air legislation in the more distant future.

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Cobb, C. B. *Clean Air Act Brings Both Product Fungibility Problems and Strategic Opportunities.*

Emmrich, G. *Octenar, An Economical Process for Producing Low Benzene Gasoline.*

Keesom, W. H., et al. *Olefins Utilization and Oxygenate Production.*

Ragsdale, R. *The Economics of Reformulated Gasoline Production.*

Unzelman, G. H. *Refining Options and Gasoline Composition, 2000.*

Wakim, J. M. *MTBE Supply/Demand Impact on the Refiners in the 1990's.*

APPENDIX A

THE REFINING PROCESS

THE REFINING PROCESS

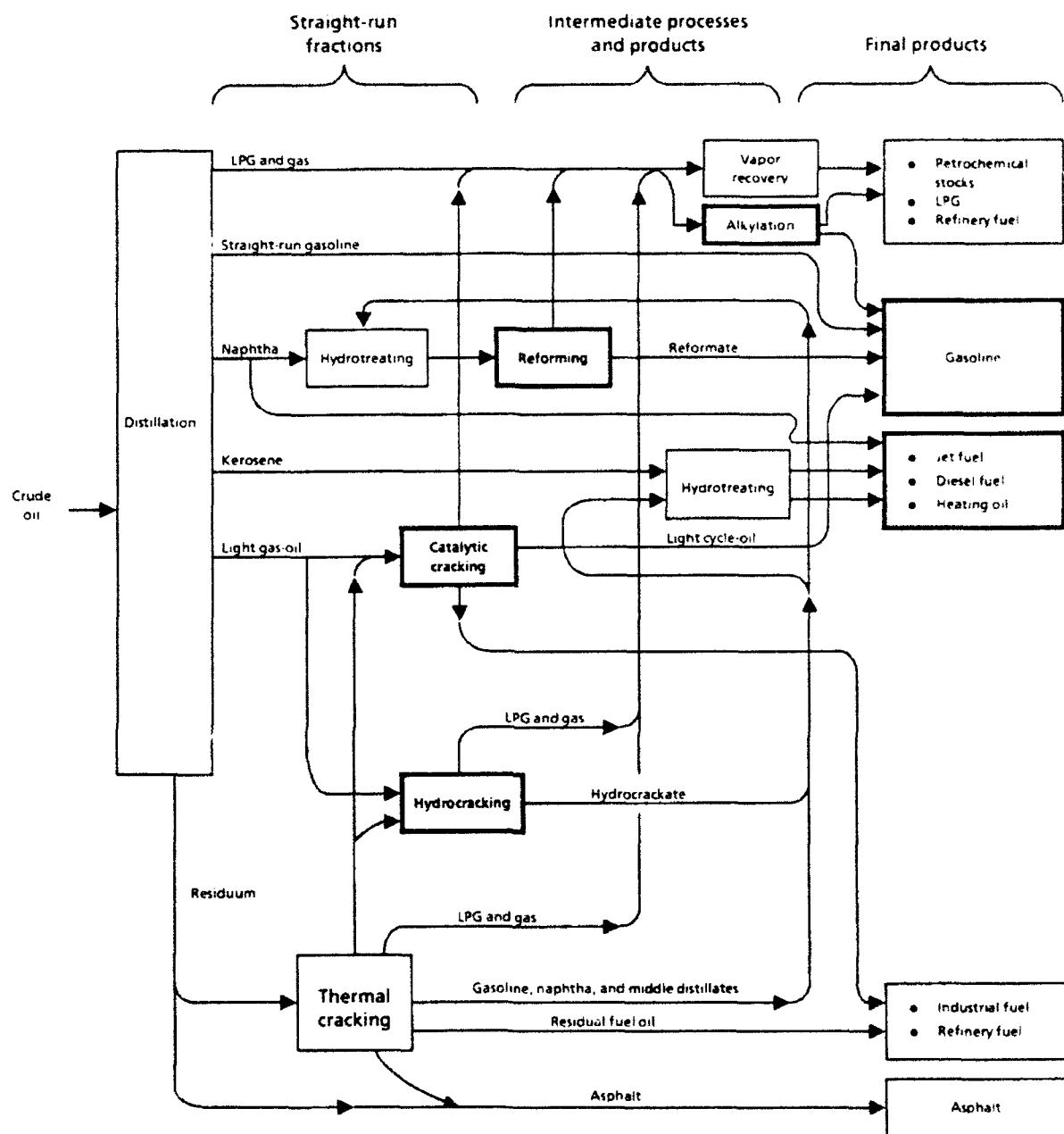
Refining is the manufacturing process that produces useful products from crude oils. Crude oil refining is a complex process. Major changes to the manufacturing processes associated with gasoline and diesel fuels affect the production of other petroleum products because of the many interactions within a refinery. Figure A-1 illustrates the flow of a typical complex domestic refinery. As complicated as the figure is, it represents only a very few of the many distinct intermediate and final product streams found in major U.S. refineries.¹

Refiners start by distilling crude oil – separating its components based upon boiling ranges – into “straight-run fractions.” Most straight-run fractions are no longer sold as final products; they undergo a series of other processes to improve quality and value before they are blended into salable petroleum products. Some of those processes cause profound chemical changes to the compounds that pass through them. Refineries also produce complex streams of “intermediate products” that are produced by one process and consumed by another, before blending the remaining intermediates into final products.

DISTILLATION

Crude oil refining starts in the distillation towers where the oil is separated into various straight-run products or fractions, which are mixtures of compounds with similar boiling ranges. Figure A-2 illustrates the distillation curve for a typical crude oil. Crude oils differ in the percentage of the various fractions they yield when distilled, and distillation yields in a refinery can be further adjusted by drawing off products with different boiling ranges. Heavy crude oils have steeper distillation curves; that is, they yield higher percentages of the heavy fractions: residual fuel oil and heavy gas-oil. Lighter crude oils yield proportionally more straight-run gasoline and naphtha. “Distillates” are the intermediate oil products that fall into the middle boiling range. (The boiling points shown are rough estimations, because individual

¹Readers who are familiar with the refining process can safely skip this appendix. We discuss refiner responses to the 1990 Clean Air Act (CAA) Amendments in Chapter 3.

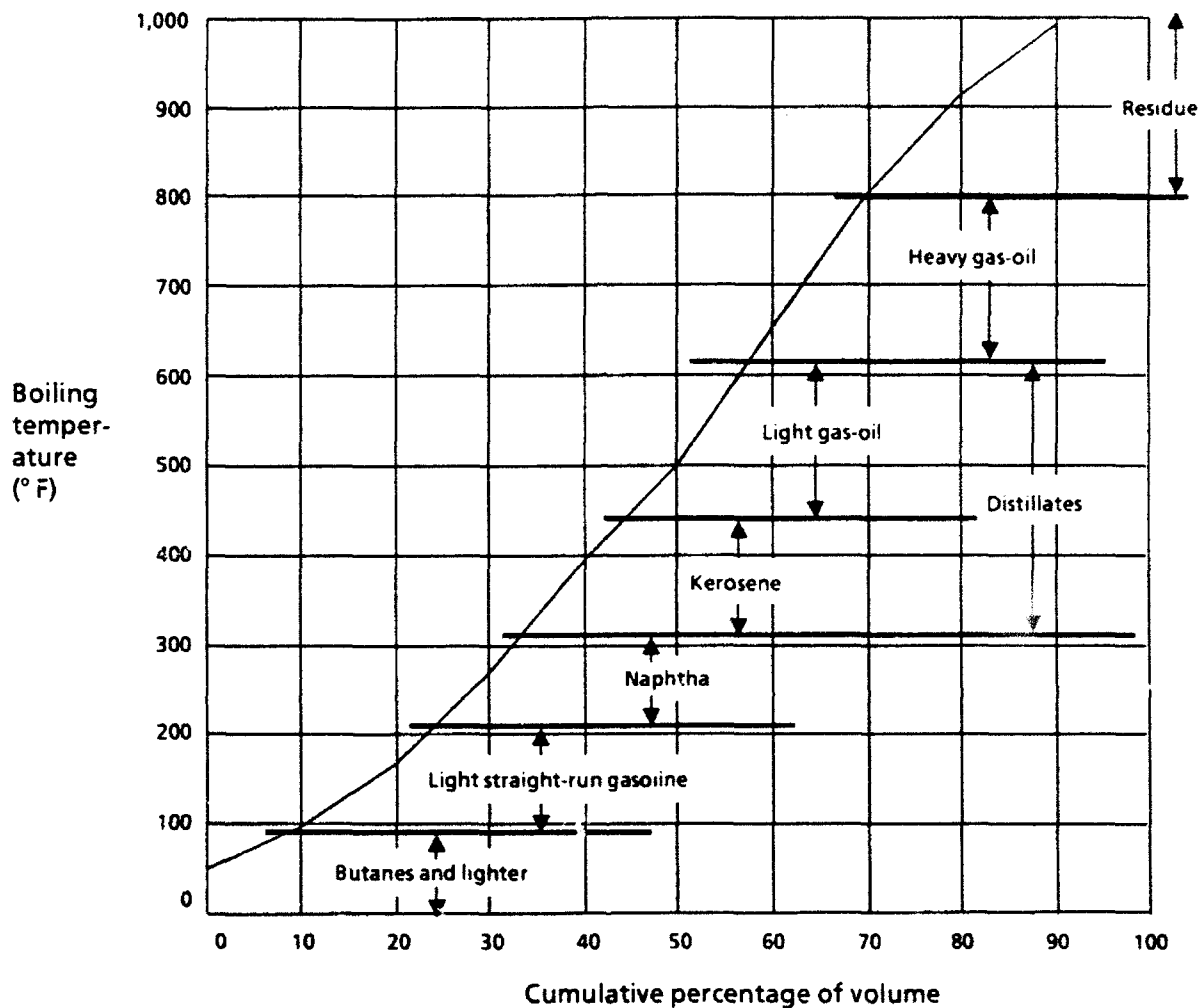


Note: LPG = liquified petroleum gas.

Source: J. H. Gary and G. E. Handwerk, *Petroleum Refining; Technology and Economics*. Marcel Dekker, N.Y. 1975, p. 3.

FIG. A-1. COMPLEX DOMESTIC REFINERY PRODUCT FLOW

refiners may draw products off at different boiling points to meet their own requirements.)



Source: W. L. Leffler, *Petroleum Refining for the Non-technical Person*, Petroleum Publishing Company, Tulsa, Okla., 1979, p. 7.

FIG. A-2. CRUDE OIL FRACTIONS FROM A REPRESENTATIVE CRUDE OIL

For example, JP-4 fuel is a mixture of hydrocarbons whose boiling points fall roughly between 200° F and 600° F (more precisely, the specification requires that at least 20 percent of the hydrocarbons boil below 290° F and no more than 10 percent boil above 550° F). Therefore, JP-4 generally consists of a mixture of naphtha with some kerosene and other distillates. The JP-8 and JP-5 fuels are different mixtures consisting of hydrocarbons with a higher boiling point, (at least 10 percent below

400° F and nothing above 550° F). Since JP-8 and JP-5 contain more kerosene and gas-oil with much less naphtha, they are termed "kero-jet" fuel.

Crude oil yields are determined largely by the chemistry of crude oils and refinery processing setups. Although we can describe refinery processes in general terms, each refinery has its own unique implementation and setup of those processes. Those processes drive the manner in which a refinery manufactures finished products. Despite the fact that yields vary widely between refineries, the given setup of refineries means that overall yields vary little over time. As shown in Table A-1, domestic yields of the major refinery product categories changed little between 1985 and 1989.

TABLE A-1
U.S. REFINERY PRODUCTION (1985 THROUGH 1989)

Product	Percentage yields				
	1985	1986	1987	1988	1989
JP-4	1.5	1.3	1.4	1.4	1.4
Kero-jet (JP-5/JP-8/other)	7.2	7.6	7.8	7.7	7.8
Total jet fuels	8.7	8.9	9.2	9.1	9.2
Kerosene	0.7	0.6	0.5	0.5	0.5
Distillate fuels	19.5	19.3	18.7	19.0	19.1
Gasoline	46.7	46.5	46.8	46.3	45.9
Other	24.4	24.7	24.8	25.0	25.3
Total petroleum products	100.0	100.0	100.0	100.0	100.0

CONVERSION PROCESSES

In addition to distillation — a physical process that produces no chemical changes in the raw material — refineries employ processes that change the chemistry of petroleum compounds to meet product specifications. As shown in Figure A-1, very few straight-run products are sold as is; most undergo additional processing.

The intermediate fractions resulting from distillation require additional processing to meet quality specifications. At one end of the process spectrum are treatment processes that remove impurities, increase gasoline octane, and otherwise make minor changes to improve the product's ability to meet specifications. At the other end of the spectrum are the conversion processes that employ heat, pressure, and catalysts to break down heavy molecules into lighter, more valuable ones.

Three basic conversion processes exist: fluid catalytic cracking (FCC), hydrocracking, and thermal cracking. Catalytic cracking "cracks" intermediate-weight fractions using heat and pressure in the presence of catalysts. Hydrocracking is essentially catalytic cracking in the presence of hydrogen; it is an extremely flexible process that can convert a variety of medium- to heavy-weight fractions into lighter weight fractions. Thermal cracking uses heat without catalysts; refiners use it to crack the heaviest crude oil fractions.

The FCC unit – so called because the powdered catalyst acts like a fluid – produces a relatively high proportion of unsaturated hydrocarbons, aromatic compounds, and olefins with less stable double bonds. Because aromatics are reactive – combine readily with other compounds – they are implicated in the formation of smog and hence limited in reformulated gasoline. Despite its quality drawbacks, FCC is more prevalent than hydrocracking. Measured by the volume processed, 87 percent of domestic refining capacity has FCC capacity, while only 46 percent has hydrocracking capacity.² Of the 194 operating refineries in the United States, we can characterize 129 as complex. Those 129 – which have a catalytic cracker, a hydrocracker, or both – process 92 percent of all the crude oil refined domestically.

Hydrocracking is the conversion process that produces the highest quality products; it removes sulfur impurities and produces fully saturated, and hence more stable, products.³

²Those percentages were obtained by dividing total conversion capacity by total atmospheric distillation capacity.

³Saturated hydrocarbons contain a full complement of hydrogen atoms with no double or triple bonds. Unsaturated compounds have a lower ratio of hydrogen atoms to carbon atoms with at least one double or triple bond.

Thermal cracking is used to convert the very heaviest straight-run products. The thermal cracker's output typically undergoes further processing to yield usable products.

Refiners can change the yields and qualities of output from their conversion units by varying their operating parameters: temperature, pressure, and catalyst type. Generally, the higher the severity (a combination of temperature and pressure), the higher the yield of light, valuable products, but the greater the cost.

QUALITY-IMPROVEMENT PROCESSES

In addition to cracking processes, refineries use other processes to improve product characteristics. For example, hydrotreating is a less severe form of hydrocracking that minimizes the conversion of heavy- into light-weight molecules but removes impurities, particularly sulfur. Another important finishing process is catalytic reforming, which alters the chemistry of certain intermediate naphtha compounds to improve their octane rating. The reforming process is a major source of aromatic compounds in gasoline; reforming can increase the aromatic content of its feedstock from 10 percent to about 60 percent, depending on severity. In fact, catalytic reformers are intended to maximize the yield of high-octane aromatics.

GASOLINE BLENDING

Gasoline production is essentially a blending operation of intermediate fractions from a wide variety of refinery processes. Starting with simple distillation of relatively low boiling point compounds – straight-run gasoline and naphtha – refiners can apply both catalytic cracking and hydrocracking to produce even more gasoline blending components. Those components are treated using a variety of processes, including hydrotreating, reforming, and alkylation to reduce impurities and improve octane rating.

By adding more requirements to gasoline specifications, the 1990 CAA Amendments will make the gasoline manufacturing process even more complex. For example, the mandated oxygen levels can be met only by adding alcohols or ethers – so-called oxygenates – to gasoline. Refiners will have to add more, new refining units to produce sufficient oxygenates to meet the law's requirements. Similarly, refiners will have to modify and possibly add other refining processes to reduce the

levels of aromatics in gasoline. Lead is already on the way out and should pose no significant production problems.

JET FUEL BLENDING

Jet fuel manufacture is a simpler process. The kero-jet fuels – JP-5, JP-8, and commercial jet fuels – are made primarily by blending straight-run distillates in the kerosene boiling range. Because distillates come from a different “cut” of crude oil than do gasoline components, there is generally minimal interaction between gasoline blending and jet fuel blending. Nevertheless, as refiners increase the throughput and severity of their conversion processes, gasoline yields increase, usually at the expense of distillate yields.

Currently, the JP-4 jet fuel used domestically by the Air Force is a mixture of naphtha and kerosene; therefore, it competes and interacts more directly with naphtha-based gasoline. The JP-4 is a wide boiling-range material that extends through the naphtha and kerosene boiling ranges. The wide boiling range permits great flexibility to the refiner in blending kerosene, naphtha, and light straight-run gasoline. That flexibility means that JP-4 competes more directly with gasoline blendstocks and has the potential to be more directly affected by changes in gasoline processing.

Refiners process jet fuel blending components through one or more of a variety of mild treatment processes to remove sulfur compounds, other reactive materials, and surfactants, which would otherwise allow water to remain in suspension in the fuel. Catalytically and thermally cracked distillates are generally not included in jet fuel blending for a number of reasons. First, cracked distillates contain aromatics that reduce smoke point, a specification that measures how cleanly the fuel burns. Aromatics are also explicitly limited in jet fuel specifications to 20 percent or 25 percent of total volume. Second, cracked distillates contain olefins, a class of non-naturally occurring and relatively unstable hydrocarbons that could cause the jet fuel to fail another specification, the thermal stability test. On the other hand, refiners use hydrocracked material in jet fuel since it contains very small amounts of aromatics and olefins.

APPENDIX B

REFINERY MODEL: BASE SCENARIO CALIBRATION

TABLES

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B-4. Refinery Model Capacities: Base Case	B-7

REFINERY MODEL: BASE SCENARIO CALIBRATION

We used the Department of Energy's Refinery Yield Model Spreadsheet System (RYMSS), with some modifications, to model a base refining scenario (i.e., *base case*) and two worst case oxygenated/reformulated gasoline scenarios. Our original intent was to determine the effects of the worst case scenarios on jet fuel quality and availability and then to determine the incremental effects of more realistic scenarios. However, since the effects of even the worst case scenario on jet fuel are negligible, we had no need to model additional cases. However, we did test variations on our two primary worst case scenarios. Since those variations did not alter our conclusions, we present only the two primary scenarios for clarity – Case 1 and Case 2.

In this appendix, we summarize the major *base case* inputs to RYMSS. We ran a base case to calibrate the model against actual domestic refinery runs for the base year (1989) in as much detail as the data afford. The year 1989 represents a typical year for the U.S. refining industry prior to the imposition of new gasoline volatility regulations and prior to enactment of the Clean Air Act (CAA) Amendments in 1990.

To simplify our analysis, we treat the nearly 200 domestic refineries as one large refinery. Essentially, this assumes that intermediate refinery products are free to move between refineries. Because a market for such intermediate products exists in the U.S., that assumption is not overly restrictive. Nevertheless, we recognize that logistical and cost barriers make completely free movement of intermediate products among all domestic refineries impossible.

In general, we constrained all of the model runs (base case and others) to produce no more than the total volume of kerosene and jet fuel produced by U.S. refineries in the base year. The model also aimed to produce the same amount of residual fuel oil but could produce more if necessary (which happened only in Case 1). We set the operating parameters (refinery unit operating severities and percent utilizations) of both the catalytic reformer and fluid catalytic cracker (FCC) to produce the base year gasoline volume while simultaneously meeting the base year octane and Reid vapor pressure (RVP) specifications.

Table B-1 illustrates the overall outputs of the base case calibration compared to actual 1989 refinery outputs. The only difference is the slightly greater volume of distillate produced by the model. The close agreement between the model result and actual refinery output is remarkable from a simple model like RYMSS.

TABLE B-1
REFINERY MODEL OUTPUTS: BASE CASE

Finished products	Volume (kBD)		
	Actual (1989)	Model	Change
Gasoline	6,988	6,988	0
Naphtha-jet fuel (JP-4)	206	206	0
Kero-jet fuel	1,197	1,197	0
Kerosene	74	74	0
Diesel/heating oil	2,899	2,885	14
Residual fuel	954	954	0

Note: kBD = thousand barrels per calendar day.

Having calibrated the base case against the actual base year, the *changes* between the base case and the worst case scenarios become more important than absolute values. Despite the simplifications made in order to model the future course of the domestic refining industry, the changes provide useful information with which to judge the eventual impacts of the 1990 CAA Amendments on distillate fuels.

The crude oil inputs, shown in Table B-2, are based on actual refinery inputs, simplified by choosing one or two major crude oils from each of the producing countries that exported to the United States in the base year. We arrived at that particular slate of crude oils using the actual volume from each country and within that, balancing the mix of Saudi Light, Saudi Heavy, Isthmus, Maya, West Texas Intermediate, and West Texas Sour to make the API gravity¹ of the model's slate equal the gravity of the original slate. The weighted average sulfur content of the

¹API gravity is an arbitrary scale expressing the gravity or density of crude oil and liquid petroleum products.

model's simplified crude oil inputs is similar to the actual weighted average sulfur content.

TABLE B-2
CRUDE OIL INPUTS: BASE CASE

Crude oil inputs	Nation of origin	kBD	API gravity	Sulfur weight (%)
Saudi Light	Saudi Arabia	1,377	33.40	1.20
Saudi Heavy	Saudi Arabia	344	27.90	2.80
Qatar	Qatar	41	41.70	1.30
Hassi Messaoud	Algeria	80	42.80	0.20
Forcados	Nigeria	1,159	29.70	0.20
Gabon	Gabon	49	31.00	0.10
Minas	Indonesia	290	34.50	0.10
Miri	Brunei	13	36.20	0.10
Bachaquero	Venezuela	631	16.80	2.40
Oriente	Ecuador	90	29.20	1.00
Isthmus	Mexico	475	33.00	1.60
Maya	Mexico	316	22.00	3.50
Brent	UK	287	38.00	0.30
Canadian Lloydminster	Canada	510	27.00	2.20
Canadian Condensate	Canada	128	55.00	0.02
Alaskan North Slope	United States	1,874	26.60	1.03
West Texas Intermediate	United States	1,798	40.20	0.38
West Texas Sour	United States	3,941	34.00	1.35
Model total		13,401	32.14 ^a	1.16 ^a
Actual total (1989)		13,401	32.14 ^a	1.06 ^a

Notes: kBD=thousand barrels per day.

^a Weighted average.

Table B-3 shows inputs of intermediate products, which equal actual 1989 purchases. Net product purchases consist of imports from overseas refineries plus some purchases from domestic petrochemical plants.

TABLE B-3
INTERMEDIATE PRODUCT INPUTS: BASE CASE

Intermediate product inputs	kBD
Naphtha	5
Distillate/gas-oil	511
Other hydrocarbons (MTBE, etc.)	60
N-Propane	11
N-Butane	148
Isobutane	151
Pentane	184
Gasoline blending components	42
Total intermediate products	1,112
Actual total (1989)	1,112
Total refinery input: crude oil and products	14,513

Notes: MTBE = methyl tertiary butyl ether. kBD = thousand barrels per day.

Table B-4 shows the operating capacities and percentage utilization of the refinery process units. Those values reflect actual utilization rates in the base year.

We chose to use RYMSS rather than a linear programming approach because we are interested primarily in volume and quality effects, rather than price effects. While linear programming normally assumes that prices remain stable (are exogenous variables), it is clear that gasoline prices will increase as a result of reformulation.

TABLE B-4

REFINERY MODEL CAPACITIES: BASE CASE

Charge capacities	Operable capacity (kSD)	Percentage utilized	Constrained capacity (kSD)
Process units			
Atmospheric crude unit	15,913	84	13,400
Fluid coker	800	84	673
Delayed coker	800	84	673
Visbreaker	508	84	427
Fluid catalytic cracker (FCC)	5,441	100	5,441
Distillate hydrocracker	1,192	72	864
Residuum hydrocracker	90	72	65
Reformer	3,896	67	2,600
Naphtha desulfurization	7,153	84	6,023
Distillate desulfurization	954	84	803
Fuel oil desulfurization	954	84	803
Residuum desulfurization	477	84	402
Other			
Alkylation	1,166	92	1,050
Aromatic recovery	240	90	216
Butane isomerization	298	90	268
Pentane/hexane isomerization	298	90	268

Note: kSD = thousand barrels per stream day (except that atmospheric crude unit is kBD).

APPENDIX C

REFINERY MODEL: CASE 1

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REFINERY MODEL: CASE 1

The Case 1 model demonstrates that, despite severe constraints, jet fuel availability improves and quality changes only slightly when refiners purchase additional ethers to meet the 1990 Clean Air Act Amendments. Both Case 1 and Case 2 explore the effects of blending *all* domestic gasoline so that it meets the most stringent specifications in the Environmental Protection Agency's so-called "Simple Model." Table C-1 lists the specifications. The constraints are admittedly unrealistic and are meant to encompass the most extreme possibilities. However, neither scenario – as extreme as both are – reduces distillate fuel quality or availability. We can be confident, therefore, that the actual situation, which we know will fall somewhere inside that envelope, will reduce neither quality nor quantity to any significant extent.

TABLE C-1
GASOLINE PROPERTIES

Specifications	Case 1	Base case	Change
Pool octane ^a	88.7	88.7	0.0
Reid vapor pressure	7.2	9.7	(2.5)
Benzene (volume percentage)	1.0	1.6	(0.6)
Aromatics (volume percentage)	25.0	28.8	(3.8)
Oxygen (weight percentage)	2.70	0.16	2.54

^a Octane is the average of research octane and motor octane.

Like the base case, Case 1 constrains jet fuel and kerosene production to equal the actual base year output volume and sets the gasoline production parameters to produce the same volume of gasoline.

Case 1 differs from Case 2 by assuming that U.S. refiners *purchase* all required oxygenates rather than manufacture them internally. That is, oxygenates are manufactured by non-refiners or imported. We used methyl tertiary butyl ether (MTBE) as the only oxygenate. Table C-2 shows that to meet the Case 1 constraints,

we had to reduce both reformer severity and catalytic cracker utilization below the base case.

TABLE C-2
GASOLINE PROCESS PARAMETERS

Parameters	Case 1	Base case	Change
Reformer utilization	68.5	66.7	1.8
Reformer severity	92.5	104.7	(12.2)
FCC utilization	66.5	99.8	(33.3)
FCC severity	70.0	68.5	1.5

Note: FCC = fluid catalytic cracker.

Table C-3 summarizes the resulting Case 1 refinery balance: what goes in and what comes out in the new scenario compared with the base case. We set lower crude oil runs to offset increased oxygenate purchases. Table C-4 details the crude oil changes between Case 1 and the base case. The major change to unfinished product imports is the increased import of MTBE for direct blending to gasoline. The reduced conversion of crude oil to gasoline blending components allows some distillate purchases to be replaced with manufactured distillate.

Tables C-5 and C-6 detail the effects of the refinery process changes on distillate fuel composition and properties. The only major change is the reduced proportion of light cycle oils blended into diesel fuels and home heating oil, a direct result of lower catalytic cracker use. Case 1 produces slight *improvements* in the quality of diesel fuel and home heating oil; changes to jet fuels are insignificant.

Table C-7 presents a detailed look at the distillate pool balance, showing the sources and uses of the intermediate product streams that go into jet fuel and other distillate fuels. The major changes are caused by the cutback in refinery conversion and the reduction in straight-run products caused by the reduction of crude oil runs (less crude oil into the atmospheric distillation unit).

TABLE C-3

REFINERY BALANCE: CASE 1 VERSUS BASE CASE

Refinery inputs and outputs	Volume (kBD)		
	Case 1	Base case	Change
Refinery inputs			
Imported crude oil	4,788	5,788	(1,000)
Domestic crude oil	7,613	7,613	0
Intermediate products			
Naphtha/gasoline	42	47	(5)
MTBE	1,037	60	977
Distillate	439	511	(72)
Other	494	494	0
Total inputs	14,413	14,513	(100)
Refinery outputs			
Light ends	732	729	3
Gasoline	6,988	6,988	0
JP-4	206	206	0
Kero-jet	1,197	1,197	0
Kerosene	74	74	0
Diesel/Heating oil	2,885	2,885	0
Residual fuel	969	954	15
Other	1,295	1,315	(20)
Total outputs	14,346	14,348	(2)
(Gain)/loss	67	165	(98)
Balance	14,413	14,513	(100)

Note: kBD = thousand barrels per day.

TABLE C-4

CRUDE OIL INPUTS: CASE 1 VERSUS BASE CASE

Crude oils	Volume (kBD)			API gravity	Sulfur weight (%)
	Case 1	Base case	Change		
Saudi Heavy	291	344	(53)	27.90	2.80
Bachaquero	0	631	(631)	16.80	2.40
Maya	0	316	(316)	22.00	3.50
Other imported	4,497	4,497	0	32.80	0.90
Domestic	7,613	7,613	0	33.64	1.04
Total crude oil	12,401	13,401	(1,000)	33.20 ^a	1.03 ^a

Notes: API gravity is an arbitrary scale expressing crude oil density. kBD = thousand barrels per day.

^a Weighted average.

TABLE C-5
DISTILLATE POOL CONSTITUENTS

Constituents	Volume percentage		
	Case 1	Base case	Change
Naphtha-jet (JP-4)			
Butane	2	2	0
Naphtha	98	98	0
Total	100	100	0
Kero-jet			
Kerosene	77	79	(2)
Hydrocrackate	13	14	(1)
Naphtha	10	7	3
Total	100	100	0
Diesel/heating oil			
Light cycle oils/coker	9	33	(24)
Gas-oil	70	46	24
Kerosene	21	16	5
Naphtha	0	5	(5)
Total	100	100	0

TABLE C-6
DISTILLATE PROPERTIES

Constituents	Case 1	Base case	Change
Naphtha-jet (JP-4)			
API gravity ^a	46.9	46.9	0.0
Above min.	1.9	1.9	0.0
Below max.	10.1	10.1	0.0
Sulfur (weight percentage)	0.0	0.0	0.0
Below max.	0.3	0.3	0.0
Reid vapor pressure	2.8	2.8	0.0
Above min.	0.8	0.8	0.0
Below max.	0.2	0.2	0.0
Kero-jet			
API gravity ^a	41.4	41.1	0.3
Above min.	4.4	4.1	0.3
Below max.	9.6	9.9	(0.3)
Sulfur (weight percentage)	0.3	0.3	0.0
Below max.	0.0	0.0	0.0
Flash point blend index	303	291	12
Below max.	450	462	(12)
Diesel/heating oil			
API gravity ^a	36.5	33.7	2.8
Above min.	6.5	3.7	2.8
Below max.	1.5	4.3	(2.8)
Sulfur (weight percentage)	0.4	0.4	0.0
Below max.	0.1	0.1	0.0
Flash point blend index	72	102	(30)
Below max.	200	170	30

^a The higher the API gravity, the lighter the fuel.

TABLE C-7
DISTILLATE POOL BALANCE

Distillate fuel constituents	Volume (kBD)		
	Case 1	Base case	Change
Gas-oil			
Sources			
Purchases	439	511	(72)
Straight-run	1,568	1,679	(111)
Uses			
Fluid catalytic cracker (FCC)	0	(852)	852
To			
Diesel/heating oil	2,007	1,338	669
Kerosene			
Sources			
Straight-run	1,626	1,721	(95)
Uses			
Residual fuel blending	0	(236)	236
Petrochemicals	(18)	(18)	0
To			
Kero-jet	919	948	(29)
Kerosene	74	74	0
Diesel/heating oil	615	445	170
Hydrocrackate			
Sources			
Hydrocracker	162	162	0
To			
Kero-jet	162	162	0

Note: kBD = thousand barrels per day.

TABLE C-7
DISTILLATE POOL BALANCE (Continued)

Distillate fuel constituents	Volume (kBD)		
	Case 1	Base case	Change
Naphtha			
Sources			
Purchases	0	5	(5)
Straight-run	2,373	2,476	(103)
Aromatics recovery	102	34	68
Uses			
Reformer	(1,974)	(1,904)	(70)
Petrochemicals	(167)	(167)	0
To			
JP-4	202	202	0
Kero-jet	116	87	29
Diesel/heating oil	16	155	(139)
Light cycle oils/coker			
Sources			
Coker/visbreaker	275	274	1
Fluid catalytic cracker (FCC)	836	1,537	(701)
Uses			
Hydrocracker	(864)	(864)	0
To			
Diesel/heating oil	247	947	(700)
Other blending components			
Butane to JP-4	4	4	0
Total products			
JP-4	206	206	0
Kero-jet	1,197	1,197	0
Kerosene	74	74	0
Diesel/heating oil	2,885	2,885	0

Note: kBD = thousand barrels per day.

APPENDIX D

REFINERY MODEL: CASE 2

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REFINERY MODEL: CASE 2

The Case 2 model further demonstrates that jet fuel availability will increase and quality changes will be insignificant despite the most severe constraints. The only difference between Case 1 and Case 2 is that the latter assumes that domestic refiners *manufacture* all oxygenates; none is purchased or imported. Case 2, like Case 1, is an extreme scenario that places an envelope around the likely future; it is almost certain that the domestic industry will be unable to produce all of the oxygenates initially required. Furthermore, even in the long run, many observers believe that foreign imports from plants in the Middle East, South America, and Canada are likely to continue to remain competitive with U.S. suppliers.

Like the base case, Case 2 constrains jet fuel and kerosene production to equal the actual base-year output volume and sets the gasoline production parameters to produce an equal volume of gasoline. Case 2 assumes the same gasoline specification limits as Case 1, as shown in Table D-1.

TABLE D-1
GASOLINE PROPERTIES

Specifications	Case 2	Base case	Change
Pool octane ^a	88.7	88.7	0.0
Reid vapor pressure	7.2	9.7	(2.5)
Benzene (volume percentage)	1.0	1.6	(0.6)
Aromatics (volume percentage)	25.0	28.8	(3.8)
Oxygen (weight percentage)	2.70	0.16	2.54

^a Octane is the average of research octane and motor octane.

To meet clean gasoline requirements, we reduced both reformer utilization and severity; we also reduced catalytic cracking utilization, as shown in Table D-2. Table D-3 summarizes the resulting refinery balance. Case 2 reduces crude oil runs, all Saudi Heavy, as shown in Table D-4. Net product purchases increase, however, to provide the needed raw materials – isobutylene and methanol – for manufacturing

methanol tertiary butyl ether (MTBE). While domestic refiners are capable of producing some isobutylene with the catalytic cracker and isomerization units, our scenario requires the purchase of additional quantities. Partially offsetting the increase in purchases is a decline in unfinished distillate imports; since Case 2 produces significantly more distillate than the base case, imports are no longer necessary.

TABLE D-2
GASOLINE PROCESS PARAMETERS

Parameters	Case 2	Base case	Change
Reformer utilization	62.1	66.7	(4.6)
Reformer severity	93.7	104.7	(11.0)
FCC utilization	83.0	99.8	(16.8)
FCC severity	70.0	68.5	1.5

Note: FCC = fluid catalytic cracker.

Tables D-5 and D-6 detail the effects of the Case 2 changes on distillate fuel composition and properties. The only major change is the replacement of distillate by heavy naphtha in diesel fuel and home heating oil, a direct result of lower reformer use. As in Case 1, distillate fuel qualities improve slightly while jet fuels are virtually unchanged.

Table D-7 presents a detailed look at the distillate fuel balance, showing the sources and uses of the intermediate product streams that go into jet fuel and other distillate fuels. The major changes are caused by reduced reformer activity, reduced conversion, and lower crude oil runs.

TABLE D-3

REFINERY BALANCE: CASE 2 VERSUS BASE CASE

Refinery inputs and outputs	Volume (kBD)		
	Case 2	Base case	Change
Refinery inputs			
Imported crude oil	5,644	5,788	(144)
Domestic crude oil	7,613	7,613	0
Intermediate products			
Naphtha/gasoline	42	47	(5)
MTBE	0	60	(60)
Distillate	0	511	(511)
Isobutylene	278	0	278
Methanol	353	0	353
Other	494	494	0
Total inputs	14,424	14,513	(89)
Refinery outputs			
Light ends	729	729	0
Gasoline	6,988	6,988	0
JP-4	206	206	0
Kero-jet	1,197	1,197	0
Kerosene	74	74	0
Diesel/heating oil	2,885	2,885	0
Residual fuel	954	954	0
Other	1,314	1,315	(1)
Total outputs	14,347	14,348	(1)
(Gain)/loss	77	165	(88)
Balance	14,424	14,513	(89)

Note: kBD = thousand barrels per day.

TABLE D-4

CRUDE OIL INPUTS: CASE 2 VERSUS BASE CASE

Crude oils	Volume (kBD)			API gravity	Sulfur weight (%)
	Case 2	Base case	Change		
Saudi Heavy	200	344	(144)	27.90	2.80
Other imported	5,444	5,444	0	30.31	1.23
Domestic	7,613	7,513	0	33.64	1.04
Total crude oil	13,257	13,401	(144)	32.19 ^a	1.14 ^a

Notes: API gravity is an arbitrary scale expressing crude oil density. kBD = thousand barrels per day.

^a Weighted average.

TABLE D-5
DISTILLATE POOL CONSTITUENTS

Constituents	Volume percentage		
	Case 2	Base case	Change
Naphtha-jet (JP-4)			
Butane	2	2	0
Naphtha	98	98	0
Total	100	100	0
Kero-jet			
Kerosene	80	79	1
Hydrocrackate	13	14	(1)
Naphtha	7	7	0
Total	100	100	0
Diesel/heating oil			
Light cycle oils/coker	16	33	(17)
Gas-oil	57	46	11
Kerosene	14	16	(2)
Naphtha	13	5	8
Total	100	100	0

TABLE D-6
DISTILLATE PROPERTIES

Constituents	Case 2	Base case	Change
Naphtha-jet (JP-4)			
API gravity ^a	46.9	46.9	0.0
Above min.	1.9	1.9	0.0
Below max.	10.1	10.1	0.0
Sulfur (weight percentage)	0.0	0.0	0.0
Below max.	0.3	0.3	0.0
Reid vapor pressure	2.8	2.8	0.0
Above min.	0.8	0.8	0.0
Below max.	0.2	0.2	0.0
Kero-jet			
API gravity ^a	41.0	41.1	(0.1)
Above min.	4.0	4.1	(0.1)
Below max.	10.0	9.9	0.1
Sulfur (weight percentage)	0.3	0.3	0.0
Below max.	0.0	0.0	0.0
Flash point blend index	287	291	(4)
Below max.	466	462	4
Diesel/heating oil			
API gravity ^a	36.9	33.7	3.2
Above min.	6.9	3.7	3.2
Below max.	1.1	4.3	(3.2)
Sulfur (weight percentage)	0.4	0.4	0.0
Below max.	0.1	0.1	0.0
Flash point blend index	153	102	51
Below max.	119	170	(51)

^a The higher the API gravity, the lighter the fuel.

TABLE D-7
DISTILLATE POOL BALANCE

Distillate fuel constituents	Volume (kBD)		
	Case 2	Base case	Change
Gas-oil			
Sources			
Purchases	0	511	(511)
Straight-run	1,666	1,679	(13)
Uses			
Fluid catalytic cracker (FCC)	(20)	(852)	832
To			
Diesel/heating oil	1,646	1,338	308
Kerosene			
Sources			
Straight-run	1,707	1,721	(14)
Uses			
Residual fuel blending	(258)	(236)	(22)
Petrochemicals	(18)	(18)	0
To			
Kero-jet	956	948	8
Kerosene	74	74	0
Diesel/heating oil	401	445	(44)
Hydrocrackate			
Sources			
Hydrocracker	162	162	0
To			
Kero-jet	162	162	0

Note: kBD = thousand barrels per day.

TABLE D-7
DISTILLATE POOL BALANCE (Continued)

Distillate fuel constituents	Volume (kBD)		
	Case 2	Base case	Change
Naphtha			
Sources			
Purchases	0	5	(5)
Straight-run	2,455	2,476	(21)
Aromatics recovery	95	34	61
Uses			
Reformer	(1,723)	(1,904)	181
Petrochemicals	(167)	(167)	0
To			
JP-4	202	202	0
Kero-jet	79	87	(8)
Diesel/heating oil	379	155	224
Light cycle oils/coker			
Sources			
Coker/visbreaker	274	274	0
Fluid catalytic cracker (FCC)	1,049	1,537	(488)
Uses			
Hydrocracker	(864)	(864)	0
To			
Diesel/heating oil	459	947	(488)
Other blending components			
Butane to JP-4	4	4	0
Total products			
JP-4	206	206	0
Kero-jet	1,197	1,197	0
Kerosene	74	74	0
Diesel/heating oil	2,885	2,885	0

Note: kBD = thousand barrels per day.